Defense Technical Information Center Compilation Part Notice

ADP011595

TITLE: Numerical Studies of Nonlinear Composites

DISTRIBUTION: Approved for public release, distribution unlimited

This paper is part of the following report:

TITLE: International Conference on Electromagnetics of Complex Media [8th], Held in Lisbon, Portugal on 27-29 September 2000. Bianisotropics 2000

To order the complete compilation report, use: ADA398724

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP011588 thru ADP011680

Numerical Studies of Nonlinear Composites

A. O. Pinchuk

Institute of Surface Chemistry
National Academy of Science of Ukraine
Kyiv, Nauki av., 31, Ukraine, 03022
Fax: (380) 44 264 04 46, e-mail: onmf@serv.biph.kiev.ua

Abstract

Bistable behavior of nonlinear composite structures with spherical metallic inclusions embedded in a weakly nonlinear dielectric host as well as coated spherical particles with a metallic core and a nonlinear dielectric shell have been theoretically studied using variational approach. A metal fraction of spherical inclusions causes a surface plasmon resonance. The dielectric permittivity of the nonlinear host depends on the intensity of the local electric field. It is shown that the bistable behavior can be achieved by adjusting the physical parameters of the constitutive materials.

1. Introduction

Recently, considerable attention has been devoted to composite nonlinear materials due to their potential uses as materials for optical devices [1-4]. Particularly, they can be exploited as materials for real time holographic and bistable memory devices, optical correlator devices, thresholding devices etc. The composite media with the optical bistable behavior have a particular interest as materials for optical devices. In this work the composite structures with Al spherical particles embedded in the nonlinear dielectric host as well as composite spherical particles with Al core and nonlinear dielectric shell were studied with respect to their bistable behavior based on the recently developed variational approach [1] for such media.

2. Theory

Let us consider the composite structure with the metallic spheres embedded in a weakly nonlinear dielectric host. The metallic spheres are described by the frequency dependent but field independent dielectric permittivity $\varepsilon^i(\omega) = \varepsilon' + i\varepsilon''$ while the host medium is described by the frequency independent but field dependent dielectric permittivity $\varepsilon^h(\vec{E}) = \varepsilon_0 + \chi|\vec{E}|^2$ Suppose that the concentration of the metallic inclusions is rather small, so we can neglect the interactions between them and the inclusions are small as compared with the wavelength of the incident electromagnetic waves (electrostatic approximation). Using variational approach [1] one can obtain the equation for the normalized field intensity t in the composite structure

$$f(t) \equiv t^3 - 2\mu t^2 + t = \alpha \qquad (1)$$

where

$$t \equiv \left|B^2\right| \frac{8\chi E_0^2}{5\left|\varepsilon^i + 2\varepsilon_0\right|} \quad ; \quad \mu \equiv -\frac{\mathrm{Re}\left(\varepsilon^i + 2\varepsilon_0\right)}{\left|\varepsilon^i + 2\varepsilon_0\right|} \quad ; \quad \alpha \equiv \frac{8\chi E_0^2 \left|\varepsilon^i - \varepsilon_0\right|^2}{5\left|\varepsilon^i + 2\varepsilon_0^2\right|^3}$$

$$|\mu| < 1; \quad t > 0 . \tag{2}$$

B is the complex variational parameter, $\vec{E}_0$ is the averaged electric field in the composite medium. The bistable regime in the composite structure can be achieved if the Eq. (1) has two (three) solutions for real t. It always has at least one real solution. In order for it to have three solutions, μ and α must satisfy the additional inequalities

$$\mu \geq \sqrt{3}/2 \ , \ \alpha_- \geq \alpha \geq \alpha_+ \ , \ \alpha_\pm = f(t_\pm) \tag{3}$$

where $t_\pm$ are the positions of the maximum or minimum of $f(t)$ respectively.

$$t_\pm = \frac{1}{3}\left\{2\mu \pm \left(4\mu^2 - 3\right)^{1/2}\right\} \tag{4}$$

The quantity $\left|\varepsilon^i + 2\varepsilon_0\right|$ measures how far the composite structure is from a resonant condition, where it vanishes.

Consider the next particular composite structure with the composite spheres which consist of a metallic core, characterized by the same dielectric permittivity $\varepsilon^i(\omega)$, and a concentric dielectric spherical shell having the dielectric permittivity $\varepsilon^h(\vec{E})$. Using the same variational approach [1] one can obtain the following parameters for the equations (1), which correspond to the coated sphere model

$$t \equiv \left|B^2\right| \frac{\chi E_0^2\left(5p^3 + 52p^2 + 16p + 8\right)}{5\left|\varepsilon^i + 2\varepsilon_0 - p\left(\varepsilon^i - \varepsilon_0\right)\right|} \tag{5}$$

$$\mu \equiv -\frac{\mathrm{Re}\left[\varepsilon^i + 2\varepsilon_0 - p\left(\varepsilon^i - \varepsilon_0\right)\right]}{\left|\varepsilon^i + 2\varepsilon_0 - p\left(\varepsilon^i - \varepsilon_0\right)\right|} \tag{6}$$

$$\alpha \equiv \frac{\chi E_0^2\left(5p^3 + 52p^2 + 16p + 8\right)\left|\varepsilon^i - \varepsilon_0\right|^2}{5\left|\varepsilon^i + 2\varepsilon_0 - p\left(\varepsilon^i - \varepsilon_0\right)\right|^3} \tag{7}$$

where $p = \left(r^c / r^s\right)^3$ is the core to shell radius ratio of the composite sphere.

The complex dielectric permittivity for the metallic spheres can be described by the classical Drude free-electron model or by the Drude model in combination with the Lorentz oscillator for the bound - electrons[2]

$$\varepsilon^i(\omega) = \varepsilon_0\left(1 - \frac{\omega_{pf}^2}{\omega^2 + i\omega\gamma_f} + \frac{\omega_{pb}^2}{\omega_0^2 - \omega^2 + i\omega\gamma_b}\right) \tag{8}$$

with

$$\omega_{pf,b}^2 = {N_{f,b}e^2}/{\varepsilon_0 m_0}$$

where ω_{pf}, ω_{pb} are the plasma frequencies for the free and bound electrons respectively, ${1}/{\gamma_{f,b}} \equiv \tau_{f,b}$ is the free- and bound - electron scattering time, $N_{f,b}$ in the free- and bound - electron density, e, m_0 are the electron charge and mass respectively.

3. Numerical Results

As have been mentioned above the bistable regime in the nonlinear composite structure can be achieved at the conditions expressed by inequalities (2,3). Several types of composite structures with different metallic inclusions (Al, Au, Ag) have been examined as the possible candidates for composite media. The dispersive parameters for the Drude models of the dielectric permittivity were taken from the literature [2]. In this work the bistable regime was studied for the composite structure with Al spherical inclusions described by Drude free- electron model. The following parameters were employed for the dielectric permittivity of aluminium particles $\omega_{pf} = 2.28\times10^{16}\,\mathrm{sec}^{-1}$, $\tau_f = 6.9\,\mathrm{fsec}$. The nonlinear dielectric host was chosen as a doped glass so as to enhance its cubic nonlinearity coefficient $\chi = 10^{-8}$. As can be seen from Fig. 1 the bistable regime in the particular composite structure can be achieved at the frequency $\omega \approx 7.5\times10^{15}$ rad/sec . In this case we have $\mu = 0.895$, $t_+ = 0.742$, $t_- = 0.449$, $\alpha_+ = 0.167$, $\alpha_- = 0.179$, $\chi\left|\vec{E}_0\right|^2 = 4.6\times10^{-5}$, $B = 68$ and the required field intensity to produce the bistable regime $I = (c/4\pi)\left|\vec{E}_0\right|^2 \approx 10^6\,W/cm^2$. On the Fig. 2 one can see the similar analysis for the coated sphere with Al core and the nonlinear dielectric shell. For the coated sphere there is an additional adjustable parameter p which allows to tune the bistable regime to the desired range. The parameters used in this case are the same as in the previous model with the additional $p = 0.4$. The corresponding frequency of bistability $\omega \approx 5.45\times10^{15}$ rad/sec.

4. Conclusion

In this work the bistable regime was studied for the particular composite structures with Al small spherical particles embedded in the nonlinear dielectric host, as well as for the composite coated sphere with Al core and the nonlinear dielectric shell. It is shown that the bistable behavior can be achieved by adjusting the physical parameters of the constitutive materials.

References

[1] D. Bergman, O. Levy, and D. Stroud, "Theory of optical bistability in a weakly nonlinear composite medium," *Phys. Rev. B.*, vol. 49, no. 1, pp. 129-134, January 1994.

[2] A. E. Neeves and M. H. Birnoim, "Composite structures for the enhancement of nonlinear-optical susceptibility," *J. Opt. Soc. Am. B.*, vol. 6, no. 4, pp. 787-796, April 1989.

[3] H. M. Gibbs, *Optical Bistability: Controlling Light with Light*. Orlando: H. B. Jovanovich Publisher, 1985.

[4] X. Zhang and D. Stroud, "Numerical studies of the nonlinear properties of composites," *Phys. Rev. B.*, vol. 49, no. 2, pp. 944-955, January 1994.

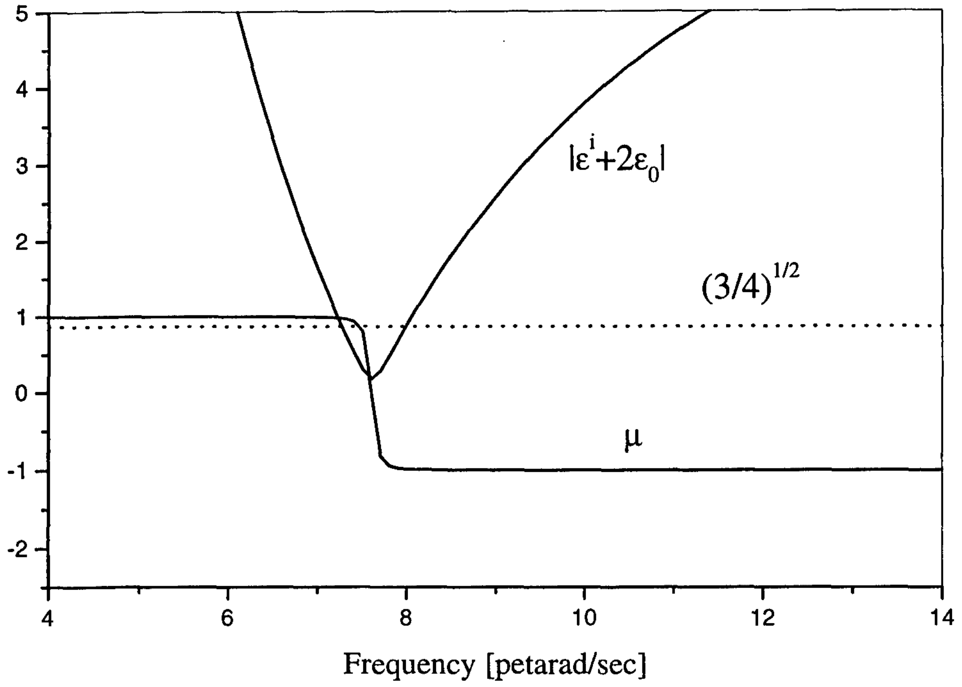

Fig. 1 The bistable regime in the nonlinear composite structure with spherical Al inclusions.

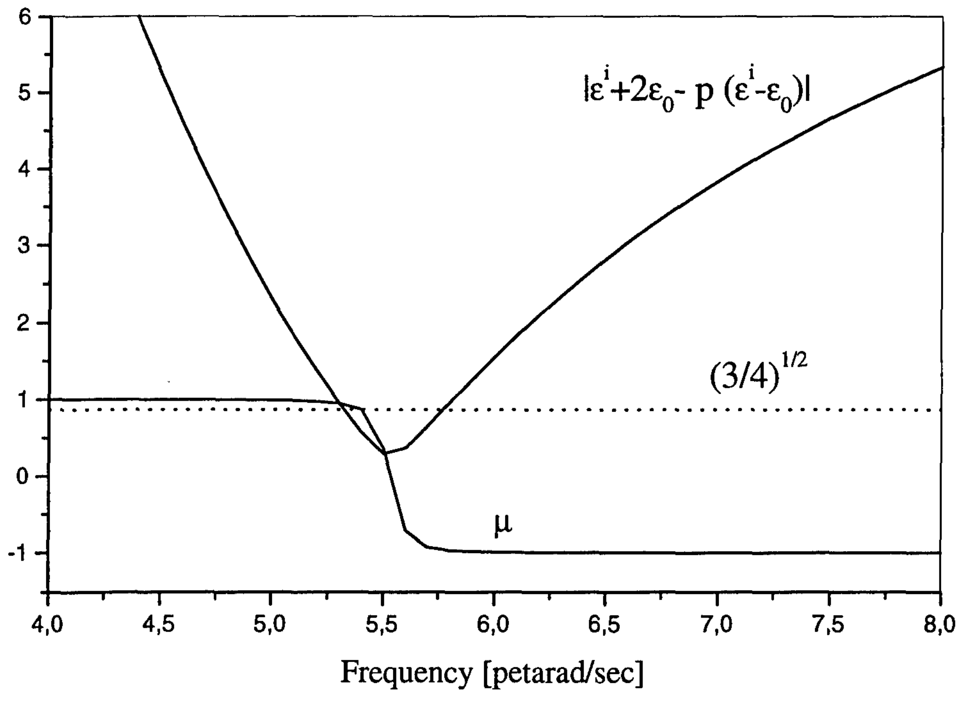

Fig. 2 The bistable regime in the nonlinear composite structure with the coated Al spherical inclusions.